## SOLAR ROTATION AND CYCLE LENGTH

BLANCA MENDOZA
*Instituto de Geofisica UNAM, Ciudad Universitaria, 04510 México D.F., Mexico*
*(E-mail: blanca@tonatiuh.igeofcu.unam.mx)*

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**Abstract.** A positive correlation is suggested between solar rotation rate and solar cycle length for cycles 12 to 20. This result seems to be opposite to recent observations in solar-type stars and the Sun and yields inverse correlations between cycle lengths and chromospheric activity, but it agrees with previous work with solar-type stars and the Sun suggesting a positive correlation between cycle length and rotation rate. Estimates of solar cycle length for the Maunder minimum suggest a length ∼17 yr.

### 1. Introduction

Direct measurements of the Sun show that areas of increased magnetic flux are accompanied by bright chromospheric Ca II H and K emission lines (Leighton, 1959; Howard, 1959). This chromospheric emission is related to small-scale field regions associated with faculae, plages and network (White *et al.*, 1992). In fact, modern Ca II fluxes show variations between 0.164 and 0.178 during the 11 yr cycle of solar activity (Wilson, 1978), while modern magnetic flux measurements also show an increase of flux from solar minimum to solar maximum (Harvey, 1994).

The relation between magnetic activity and rotation rate is expected from the standard dynamo theory which predicts increasing field amplification with increasing rotation and differential rotation (Krause and Radler, 1980). A strong positive correlation between stellar rotation rate and the overall chromospheric activity has been found by Skumanich (1972) for 16 solar-type stars (including the present Sun).

In the Sun the cycle length is a parameter closely related with the level of activity. In fact, longer cycles correspond to lower activity and *vice versa* (Lassen and Friis-Christensen, 1995), a relation involving both cycle length ($L$) and rotation period ($Pr$) has been proposed by Soon, Baliunas, and Zhang (1994). They found that for 18 solar-type stars and the Sun, through cycles 1 to 21, the amplitude of an activity cycle (ratio of the peak-to-peak activity cycle amplitude to the 25 yr averaged level of activity) and the quantity $\log(L/Pr)^2$ have an inverse correlation. They concluded that this finding was the indication of an inverse correlation between cycle length and chromospheric activity, which was later confirmed by

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Baliunas and Soon (1995) from a study of cycle lengths and Ca II fluxes for the Sun (through cycles 1 to 21) and 18 solar-type stars.

These earlier studies suggest that higher chromospheric (magnetic) activity is accompanied by both faster rotation rates and shorter cycle lengths. However, in a previous study of 46 main-sequence stars (including the present Sun), although Vaughan *et al.* (1984) confirmed the positive correlation between Ca II H and K emission and rotation rate, they also found that for those stars that in their sample have already completed a full cycle, the cycle duration was uncorrelated with the rotation velocity. Further work by Noyes, Weiss, and Vaughan (1981) on 41 solar-type stars (including the present Sun) suggested that when expressed as the ratio of chromospheric flux to total bolometric flux, the emission is well correlated with the Rossby number (the ratio between the rotation period and the convective overturn time). Also, Noyes, Weiss, and Vaughan (1981) studied 13 slowly rotating lower Main-Sequence stars (including the modern Sun), which presented Sun-like magnetic activity cycles. These authors found that for stars of a given spectral type the cycle length was inversely related to the rotation period. For the specific case of the Sun, Balthasar, Vázquez, and Wöhl (1986) analysed the complete data published in the 'Greenwich Photoheliographic Results' (GPR) for cycles 12 to 20, and found the highest solar rotation velocities around solar minimum and the lowest ones between solar minimum and maximum. This is in agreement with previous results obtained with part of the GPR data presented by Balthasar and Wöhl (1980) for the period 1940–1968 or Arévalo *et al.* (1982) for the period 1874 –1902, among others. Lustig (1983) found that velocities at the equator during solar minimum years were greater than in the neighbouring maxima. Kambry and Nishikawa (1990) found that sunspot rotation for cycles 19 to 21 varied from cycle to cycle in such a way that the average rotation velocity in the low activity cycle was higher than in the high activity cycle. Using the GPR complete data for solar cycles 12 to 20 Hoyt (1990) also reached a conclusion which are compatible with the work of Balthasar, Vázquez, and Wöhl (1986).

The purpose of this paper is to perform a study of the solar rotation rate through cycles 12 to 20, and the length of the solar cycle in order to assess the relation between solar rotation rate and solar cycle length. We present in Section 2 the data and the results, Section 3 has the discussion and Section 4 contains the conclusions.

## 2. Data and Results

In the period from 1874 through 1976 the positions of sunspot groups were measured at the Royal Greenwich Observatory from photographs nearly every day. These positions are published in the *Greenwich Photoheliographic Results.* We use the cycle-averaged data derived by Balthasar, Vázquez, and Wöhl (1986) from this historical record of the positions of sunspot groups, from the years 1874 to 1976 (cycles 12 to 20).

TABLE I
Cycle lengths and rotation rates

| Years | $L$ (years) | $RR$ (deg day$^{-1}$) |
|---|---|---|
| 1884.2 | 11.5 | $14.64 \pm 0.03$ |
| 1895.5 | 11.4 | $14.64 \pm 0.02$ |
| 1907.6 | 11.1 | $14.51 \pm 0.03$ |
| 1918.6 | 10.8 | $14.53 \pm 0.02$ |
| 1928.7 | 10.4 | $14.51 \pm 0.02$ |
| 1939 | 10.2 | $14.56 \pm 0.02$ |
| 1949.2 | 10.5 | $14.52 \pm 0.02$ |
| 1959.4 | 10.7 | $14.51 \pm 0.02$ |
| 1970.6 | 10.6 | $14.53 \pm 0.02$ |
| 1981.6 | | |

$L$ = cycle lengths (Lassen and Friis-Christensen, 1995).
$RR$ = rotation rates (Balthasar, Vázquez, and Wöhl, 1986).

A measure of solar activity is provided by the length of the solar cycle. We use the solar cycle lengths given by Lassen and Friis–Christensen (1995) with a filter 1-2-2-2-1 applied to the epochs of solar minimum from the years 1889 to 1976. The cycle lengths based on minimum epochs are preferred over cycle lengths based on epochs of maximum because the variations of amplitude of the minimum cycle lengths are significantly less than those for maximum. This is so because the determination of the epochs of sunspot maximum are less certain, particularly before 1850.

In Table 1 we present the 2 data sets used. Column 1 shows the year, column 2 the cycle length from Lassen and Friis–Christensen (1995) and Column 3 the data from Balthasar, Vázquez, and Wöhl (1986). Also, in the table appear the standard deviations of the measurements. From our Table 1 we notice that the peak-to-peak variation in rotation rates is $\sim 0.14$, whereas the maximum value of the standard deviations is $\sim 0.04$. Therefore, we assume that the trends in rotation rates reported by these authors are real.

In Figure 1 we observe the cycle length ($L$) and the rotation rates vs time. Figure 2 shows the correlations between the rotation rates and the cycle length. A loose trend appears in the rotation rates given by Balthasar, Vázquez, and Wöhl (1986), RR; the linear regressions of the data gives

$$RR = 0.08L + 13.66 \tag{1}$$

with $r = 0.69$, and with an error in the slope of $\pm 0.03$.

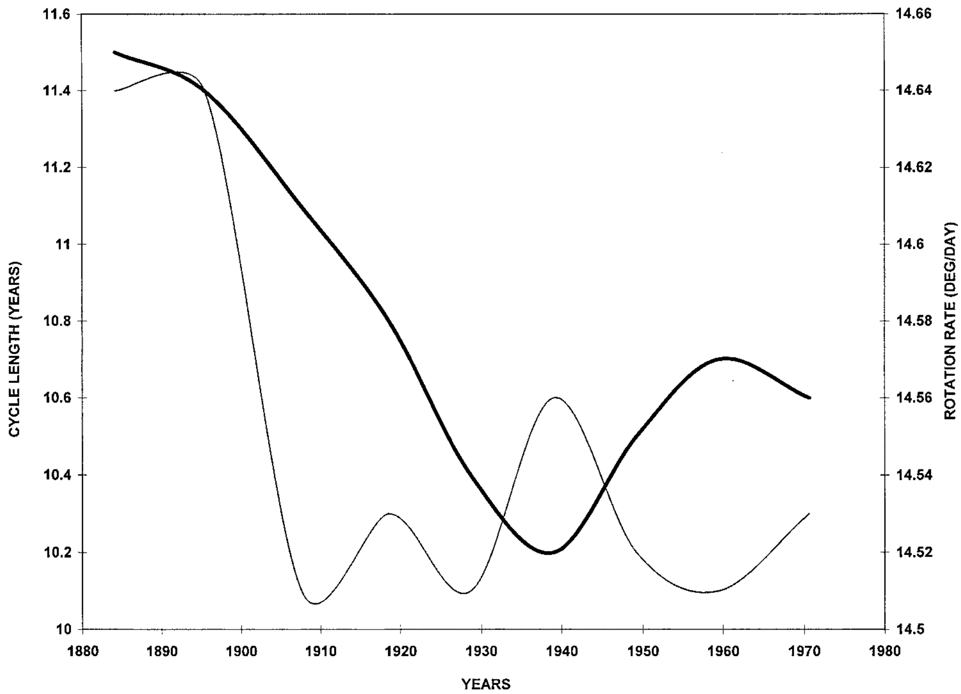


*Figure 1.* Solar cycle length in years, using a filter 1-2-2-2-1, and rotation rates in deg/day, for the years 1879 to 1975. The thick solid line is the cycle length (Lassen and Friis-Christensen, 1995), and the thin solid line is the rotation rate given by Balthasar, Vázquez, and Wöhl (1986).

Given the error in the slope of the regression line, Figure 2 does show a trend which suggests that the rotation rate is positively correlated to the activity cycle length.

## 3. Discussion

The positive correlation between solar rotation rate and cycle length suggested by Figure 2, through cycles 12 to 20, seems to be opposite to recent results indicating an inverse correlation between chromospheric activity and cycle length in the Sun (through cycles 1 to 21) and solar-type stars (Baliunas and Soon, 1995).

This finding supports previous work: Noyes, Weiss, and Vaughan (1984) studied 13 slowly rotating lower main-sequence stars (including the modern Sun), which presented Sun-like magnetic activity cycles. They found that for stars of a given spectral type the cycle length was inversely correlated with the rotation period (positively correlated with rotation rate). Balthasar, Vázquez, and Wöhl (1986) noticed that the highest sunspot rotation velocities occurred around solar minimum and the lowest velocities between solar minimum and maximum. Kambry and Nishikawa (1990) found that sunspot rotation for cycles 19 to 21 varied from

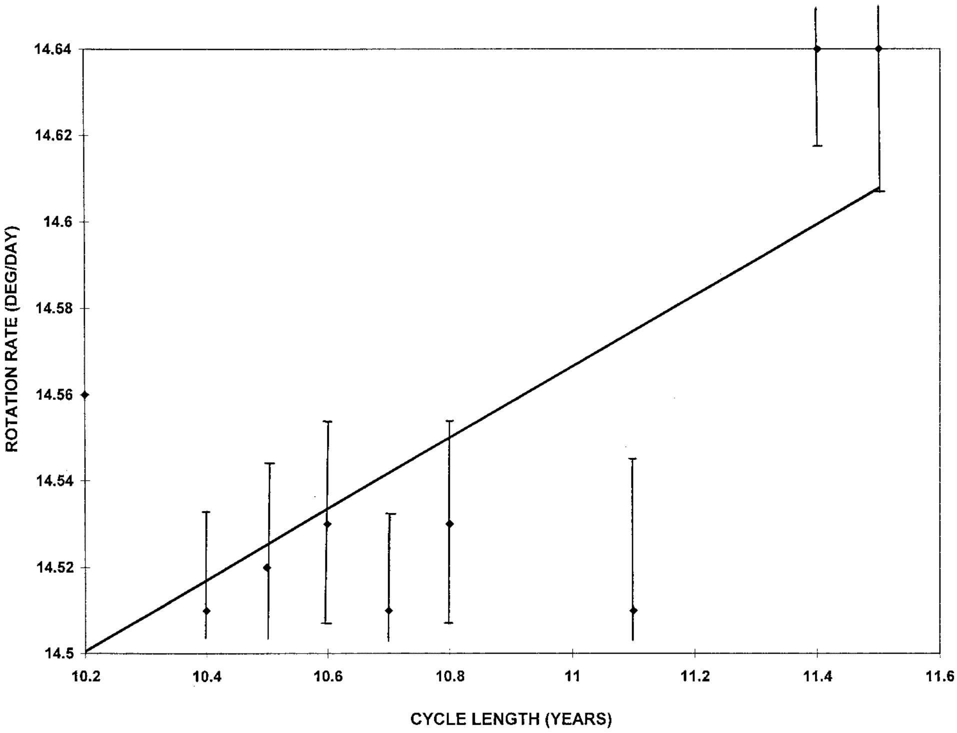


*Figure 2.* Linear regression fit between the rotation rate RR and the cycle length $L$: $RR = 0.08L + 13.66$, $r = 0.69$, the error in the slope is $\pm 0.03$. The uncertainties of the rotation rate measurements are indicated as vertical bars.

cycle to cycle in such a way that the average rotation velocity in the low activity cycle (longer cycle length) was higher than in the high activity cycle (shorter cycle length). Work carried out by Hoyt (1990) agrees with the conclusions reached by Balthasar, Vázquez, and Wöhl (1986).

Relationships found for the Sun are frequently extrapolated back to the Maunder minimum, because this epoch is considered as a limit case in solar behavior. Solar observations and theory are controversial about the rotation period during the Maunder minimum: Eddy, Gilman, and Trotter (1976) using the drawings of Hevelius found that the solar rotation rate at the beginning of the Maunder minimum was $\sim 4\%$ faster than modern values. However, Abarbanell and Wöhl (1981) re-examined the drawings of Hevelius and concluded that the rotation rate was comparable to modern values. Nesme-Ribes *et al.* (1993), studying the observations made by La Hire half a century later than Hevelius, found a slower rotation rate than we see today. There are suggestions that large-scale circulation in the form of azimuthal rolls is present in the Sun (Ribes and Bonnefond, 1990; Kosovichev, 1996). Assuming that the observed meridional photospheric motions (see review by Howard, 1996) trace these convective rolls, Nesme-Ribes and Mangeney (1992) found that the rotation rate of the Sun during the Maunder minimum was higher than during the modern maximum.

Applying the relation expressed by Equation 1 we find that if the solar rotation rate was $\sim 4\%$ faster than current values (Eddy, Gilman, and Trotter, 1976); then the cycle length should have been $\sim 17$ years. Hoyt and Schatten (1993) found that the cycle length during the Maunder minimum should have been $\sim 14$ years, while using Kocharov's (1987) carbon 14 observations, the same authors found an average length of $\sim 15$ years from 1646 to 1705. Baliunas and Soon (1995), using the inverse relation found between average chromospheric activity and solar cycle length, suggested that the Maunder minimum cycle length would have been $\sim 23$ years.

## 4. Conclusions

(1) A positive relationship between solar rotation rate and solar cycle length is suggested.
(2) This positive relation seems to be the opposite to what is reported in recent work in solar-type stars and the Sun, in which an inverse correlation is found between cycle length and chromospheric activity, and a positive correlation between chromospheric activity and rotation rate is apparent, but agrees with previous work with solar-type stars and the Sun suggesting a positive correlation between cycle length and rotation rate.
(3) Estimations of solar cycle length for the Maunder minimum indicate a length $\sim 17$ years.

## References


Abarbanell, C. and Wöhl, H.: 1981, *Solar Phys.* **70**, 197.

Arévalo, M. J., Gómez, R., Vázquez, M., Balthasar, H., and Wöhl, H.: 1982, *Astron. Astrophys.* **111**, 266.

Baliunas, S. and Soon, W.: 1995, *Astrophys. J.* **450**, 896.

Balthasar, H. and Wöhl, H.: 1980, *Astron. Astrophys.* **92**, 111.

Balthasar, H., Vázquez, M. and Wöhl, H.: 1986, *Astron. Astrophys.* **155**, 87.

Eddy, J. A., Gilman, P. A. and Trotter, D. E.: 1976, *Solar Phys.* **46**, 3.

Harvey, K. L.: 1994, in R. Rutten and C. J. Schrijver (eds.), *Solar Surface Magnetism*, Kluwer Academic Publishers, Dordrecht, p. 347.

Howard, R.: 1959, *Astrophys. J.* **130**, 193.

Howard, R.: 1996, *Ann. Rev. Astron. Astrophys.* **34**, 75.

Hoyt, D. V.: 1990, in K. H. Schatten and A. Arking (eds.), *Climate Impact of Solar Variability*, NASA Conf Publ. CP-3086, p. 42.

Hoyt, D. V. and Schatten, K. H.: 1993, *J. Geophys. Res.* **98**, 18 895.

Kambry, M. A. and Nishikawa, J.: 1990, *Solar Phys.* **126**, 89.

Kocharov, G. E.: 1987, *Astrophys. Space. Sci.* **6**, 155.

Kosovichev, A. G.: 1996, *Astrophys. J.* **461**, L55.

Krause, F. and Radler, K. H.: 1980, *Mean Field Magnetohydrodynamics and Dynamo Theory*, Pergamon, Oxford.

Lassen, K. and Friis-Christensen, E.: 1995, *J. Atmospheric Terrest. Phys.* **57**, 835.

Leighton, R. B.: 1959, *Astrophys. J.* **130**, 366.

Lustig, G.: 1983, *Astron. Astrophys.* **125**, 355.

Nesme-Ribes, E. and Mangeney, A.: 1992, *Radiocarbon* **34**, 263.

Nesme-Ribes, E., Ferreira, E. N., Sadourny, R., Le Treut, H. and Li, Z. X.: 1993, *J. Geophys. Res.* **98**, 18 923.

Noyes, R. W., Weiss, N. O. and Vaughan, A. H.: 1984, *Astrophys. J.* **287**, 769.

Noyes, R. W., Hartmann, L. W., Baliunas, S. L., Duncan, D. K. and Vaughan, A. H.: 1984, *Astrophys. J.* **279**, 763.

Ribes, E. and Bonnefond, F.: 1990, *Geophys. Astrophys. Fluid Dyn.* **41**, 171.

Skumanich, A.: 1972, *Astrophys. J.* **171**, 565.

Soon, W. H., Baliunas, S. L. and Zhang, Q.: 1994, *Solar Phys.* **154**, 385.

Vaughan, A. H., Baliunas, S. L., Middelkoop, F., Hartmann, L. W., Mihalas, D., Noyes, R. W. and Preston, G. W.: 1981, *Astrophys. J.* **250**, 276.

White, O. R., Skumanich, A., Lean, J. L., Livingston, W. C. and Keil, S.: 1992, *Publ. Astron. Soc. Pacific* **104**, 1139.

Wilson, O. C.: 1978, *Astrophys. J.* **226**, 379.